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PROPOSAL FOR EXPERIMENTAL STUDY OF THE RELATIONSHIP BETWEEN HADRONIC AND NUCLEAR SCALING AT VERY HIGH ENERGIES

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ABSTRACT

We propose to investigate the connections between scaling phenomena and the determination of structure functions in elementary particle and nuclear physics by measuring inclusive cross sections in the nuclear reaction $p + A \rightarrow (p, d, t, \pi, K) + X$.

We propose to measure the momentum and angle of the secondary in the regon 200 MeV/c - 1000 MeV/c and 90°-170° for targets ranging from Li^{6} to Ta^{181}.

I. INTRODUCTION

In the very recent past, there has been considerable progress in understanding the connections between nuclear and nucleon fragmentation, nuclear and nucleon high p_t processes, and the connection between the structure functions in the non-relativistic and extreme relativistic regimes. Examples of these investigations are the studies of "nuclear scaling" by Leksin,[1] the studies of "quasi-two body scaling" by Frankel,[2] and of the application of parton models to nuclei by Schmidt and Blankenbealer.[3] (See also A. Baldin)[4].

There is a large body of data on inclusive cross sections in nuclear processes in the reaction $A + B \rightarrow C + X$ with protons, pions, and light and heavy "relativistic" ions acting alternately as projectile, target, or detected particle. Only a small fraction of this data explores kinematic regions in which it is possible to extract the very high momentum behavior of the internal structure of the nucleus. In this area much of the pertinent data has been obtained by the experimentalists collaborating in this proposal. On the other hand there now exists in the study of very high energy elementary particle interactions a large amount of data from which one attempts to extract information on the high momentum or "quark-parton" structure of hadrons.

The problems for theory and experiment in these two fields are actually not so different. Light nuclei are after all only a few times larger than nucleons. The main difference occurs because the constituent of the nucleus, the proton, can be removed, whereas the constituent of the hadron, the quark, appears to be contained. In fact because the structure of the nucleus can be extracted from both the observation of the primary constituent and the emitted "secondary" particles, the pion or kaon, the nucleus serves as a special testing ground for methods of extracting the structure from inclusive reactions. Where, in inclusive reactions for pion and kaon production one sums over all the unobserved final states, the distinction between hadrons and nuclei is less clear.

In nuclear physics much of the data exists in regions which are not extremely relativistic so there are fewer comparisons possible with few hundred GeV hadron data. For example in the study of composite nuclei, like heavy ions, interacting with composite target nuclei, (the analogy of hadron-hadron interactions), the maximum energy per nucleon is only about 2 GeV.

This is an important reason for this proposal at Fermilab energies.

Another area in which nuclear and hadron inclusive reactions are intimately related is in the search for the appropriate scaling variables which allow for the discovery of relationships among cross sections for different particles. The more kinds of inclusive reactions that one can study, non-relativistic and relativistic, in the "fragmentation" and "high p_t" regions, the better one is able to select the pertinent variables among: e.g., the nuclear scaling variable of Leksin, the "quasi-two body scaling: variable, k_{min}, of Frankel, the transverse energy variable of the heavy ion physicists, the light cone variable, x, the Feynman variable, $p_{\parallel}/p^{*}$, the radial variable, E/E^{*}, $p_t/\sqrt{s}$, etc.

In the next section we shall attempt to illustrate the reasons for wishing to study nuclear reactions at very high energies by showing how these measurements will provide new information on nuclear structure and on the general scaling relationships that describe both hadron and nuclear structure by describing two of the many approaches that have been applied to nuclei.

The first is the empirical method of "nuclear scaing", the second is a theoretical method, that of "quasi-two body scaling".

II. PHYSICS MOTIVATIONS

A. Nuclear Scaling

The discovery of "nuclear scaling", and confirmation of these scaling phenomenon by several experiments performed over the last few years, is described in Ref. 1.

The essence of this phenomenon is as follows: in the deep inelastic nuclear reaction,

$$a + A \rightarrow b + \text{anything} \tag{1}$$

where a is the incident particle, A is the nuclear target, and b is the baryon (p, d, t ...), the inclusive spectrum of particle b is given by the invariant function

$$\rho = \frac{1}{\sigma} \cdot \frac{E}{q^2} \cdot \frac{d^2\sigma}{dq d\Omega} = C\, e^{-\frac{T}{T_o}} \simeq C\, e^{-Bq^2} \qquad (2)$$

where σ is the (a, A) inelastic cross section and E, q, T are the total energy, momentum and kinetic energy of particle b.

The main features of the invariant function (2) are:

1) The parameter T_o which characterizes the spectrum slope is at energies greater than about 1 GeV/c, independent of the energy and independent of the type of incident particle,

$$T_o \neq T_o\,(E_a,\ a),$$

In this region, T_o is also independent of the mass number of the target,

$$T_o \neq T_o\,(A)$$

2) The parameter C is also independent of both the energy and the type of incident particle

$$C \neq C\,(E_a,\ a)$$

for energies above some critical energy depending on the mass number of the nucleus A.

3) The spectrum of particle b does not depend on the characteristics of the leading particle, i.e., there is a factorization of the process.

4) The variable C is a function of mass number of the nuclear target

$$C \sim A^{2/3}$$

5) The parameters C and T_o do depend on the type and the emission angle of particle b.

Figures 1 through 3 show experimental confirmation of the above mentioned features of the invariant function. Figure 1 shows the coefficient B as a function of initial energy for proton emission angles in the range:

$$120^o < \theta_{lab} < 150^o$$

This figure taken from Ref. 1 presents the results of studying the reaction (1) with different incident particles (protons, pions, gammas). Let us note that the point marked by a star is a preliminary result of the measurement of the parameter B in $\bar{\nu}$-Ne interactions at Fermilab (Expt. 180).

The difference of the parameter B for the different nuclei as a function of the momentum of particle a is shown in Fig. 2. Finally, Fig. 3 shows the variation of (σ_p/σ_T), which is proportional to the parameter C, as a function of initial energy for different nuclei. One can see in Fig. 3 that the critical energy increases with increasing mass number and that above some critical energy the C paramter is a constant.

We can consider the above features of the invariant function (2) as being due to the limited fragmentation of the target. The correlations (3-5) are valid in the asymptotic region.

At the present time there is no one generally accepted theory of nuclear scaling (See however Section B). There are many models, among them: the representation of a nucleus as a quark bag,[5] the multiperipherical model for nuclear interactions,[6] the multiple scattering model,[7] and the model which considers the existence of fluctuons in nuclei,[8] (see also references (1), (2), (3), and (4)).

Several mechanisms that have been applied to inclusive cross sections are described by the Feynman diagrams in Fig. 4.

Figure 4(a) shows a mechanism for the interaction of the incoming particle, e.g., the proton with an off shell nucleon of momentum k via the reaction $p + p \rightarrow p + X$.[10,2]

Figure 4(b) shows a mechanism[11] for the emission of the on shell proton and the interaction of the incoming proton with the residual A-I nucleus via the total cross section $p + (A-I) \rightarrow X$.

Figure 4(c) shows a mechanism[8,12] for the interaction via elastic scattering of the incoming protom with various "clusters" of mass N.

Figure 4(d) shows a mechanism[6,13] used in parton physics, where the emitted nucleon would show small dependence, in keeping with "nuclear scaling", on the parameters of the incoming particle.

It would be interesting to check the relations (3-5) at the highest available energy because these relations are predicted to be valid in the asymptotic region.

B. Quasi-Two body Scaling

This method is described in a series of papers [2,14,15,16] and applied to the analysis of various types of data in references (17), (18), (19), and (20). The most important of these for the reader would be (2) and (14).

This theory attempts to extract structure functions for nuclei by relating the inclusive cross-section to the structure function and the measured cross-sections for the constituent-constituent interactions.

$$E\, d\sigma/d^3q = C(s,\ t)\ G(k^s_{min})$$

Here K^s_{min} is the minimum momentum, that by energy-momentum conservation, allows for the detection of an emitted particle of momentum q. k^s is the momentum of the unobserved nucleus recoiling in the final state in the configuration of lowest possible invariant mass, i.e., in what might be called the "spectator configuration". (The fact that the inclusive cross-section must depend on this variable is demonstrated in a model independent way in Ref. 14. (In a spectator picture one can also treat k as the internal momentum of the struck particle.)

$C(s, t)$ is proportional to the cross-section for the constituent-constituent reaction at the appropriate value of $s(k^s)$ and $t(k^s)$. For example for $p + A \rightarrow p + X$ in the few GeV region $C(s, t)$ is proportional to the p-p elastic cross-section.

One dramatic example Fig. 5(a) shows a plot of $d\sigma/d^3q$ vs. $q^2/2m$ displaying the feature of the gaussian falloff of the cross-section for Li^6, Be^9, and Ta^{181}. The incident energy is .8 GeV. Fig. 5(b) shows a plot of the cross-section vs. k^s, rather than q, for the case C = 1 showing that at the same angle, and up to an energy almost equal to the energy for elastic scattering in Li^6, the curves are identical in shape for all the nuclei. Fig. 5(c) shows the <u>universal</u> curve obtained when the cross-section is divided by the known experimental values of $C(s,t)$. This is but one example of the success of scaling in every example studied in $(p, d, \alpha, \ldots Ne) + A \rightarrow (p, d, t, \pi \ldots B^{11}) + X$: See the above references. One further example of "quasi-two body scaling is shown in Fig. 6 in the six reactions $(P, d, \alpha) + C \rightarrow (p, \pi) + x$. An important feature of the variable k^s as described in Ref.[14] is that <u>in the relativistic limit</u> k^s is directly expressible in terms of the light cone variable x and in the "high p_t" region reduces directly (at 90° in the cm) to the scaling variable $(p_t^2 + m_x^2/s)^{1/2}$ where m_x is the mass of the observed $(p, K, \bar{p},$ etc.,) particle. The formalism allows for simple demonstrations of a number of the hypotheses of "limiting fragmentation", etc.: e.g., that x_k for the struck constituent is the x_q for the observed particle; that the internal structure of the projectile and its final invariant mass not enter into the determination of the structure of the target in the target fragmentation region, etc.

From the standpoint of this theory the purposes of this experiment are:

1) To determine whether G(k) from 400 GeV interactions is identical with that determined at very low energies as shown in Fig.5 (c), to establish the universality of the structure function.
2) To check whether the same G(k) can be determined from constituent-constituent interactions that are either elastic or inclusive,
3) To study and compare G(k) for a variety of detected particles: p, π, K,and possibly $\bar{p}$,
4) To check the angular dependence, q dependence and A dependence of $k(p, q, \theta, A)$.

III. CALCULATION OF RATES

The expected rates can only be estimated, of course, since part of our experiment is to measure the absolute rates for the various inclusive processes under investigation. We have however carried out calculations using both of the approaches of Section II. The first method uses "nuclear scaling" to extrapolate to

400 GeV. The second uses "quasi-two body scaling" and the measured values of the cross-sections for p + p   p + X, from the Fermilab experiment of Johnson et al.[21] Both methods agree within a factor of five.

Table I shows our estimates for the rates for proton production from Ta. Shown too are our estimates for pion production.

IV. PLAN OF MEASUREMENT

Choice of targets: Li^6, Be^9, C^{12}, Cu^{64}, Ta^{181}

Typical thicknesses: one gram/cm^2

Choice of angles: Between 90^o and 170^o; Minimum of three angles.

Set-up time: We should be ready to test apparatus within two months of PAC approval

Test time (with modest beam) 125 hours

Data accumulation time: 175 hours

Beam Energy: 400 GeV preferred

V. SPECTROMETER

The spectrometer shown in Fig. 7 consists of a 1-meter long dipole and a 10Q36 quad doublet, and allows three independent measurements of a particles momentum. The solid angle acceptance is determined by the exit aperture of the dipole and is 4.3 milli-steradians.

The first measurement of the momentum is obtained from the two wire chambers which measures the emerging angle of the particle after a 20° bend in the dipole. The coulomb scattering in the first chamber dominates the momentum resolution for protons, deuterons and tritons. The 8 mm vertical spot size of the beam is a minor contributor to the momentum resolution for p, d, and t, but does make a contribution to the resolution of pions. The resolutions are tabulated in Table II for pions and protons at various momenta.

The quad doublet (probably obtainable from ANL) is preceeded by a 6 inch square scintillation counter (S1) and focusses on S2, a 1 inch square counter three feet downstream of the quads exit aperture. This magnet system has a momentum acceptance of 5% FWHM, and provides a second independent measurement of the momentum. Time of flight between S1 and S2 provide the third determination. Table I lists these accuracies assuming a time resolution of 1 ns FWHM. This complements the poor resolution obtained from the wire chambers for particles with low beta. Of course additional information is obtained from dE/dX in S1 and S2. The quads serve two additional important purposes. The area of S2 is reduced by a factor of 400, resulting in a proportional decrease in background singles rates. Also the time of flight resolution is much improved by the 20 inch reduction in the linear size of S2.

VI. SERVICES AND EQUIPMENT

To be provided by Experimenters:

1) Quadrupole doublets for spectrometer
2) Vacuum pipe for spectromer if needed
3) Scintillation hodoscope
4) Target wheel

To be provided by Laboratory

1) Keep present 4 x 120 quads in beam line, or replace with 3 x 120 quads
2) Rigging in spectrometer quads
3) Power and cool quadrupoles
4) PDP-11 and software support
5) Use of present PWC associated with E-95 spectrometer, including readout system
6) Use of tube bases and existing counter hodoscope and counters in E95 spectrometer
7) 10 CPU hours of CDC 6600 computer time
8) E95 bending magnet shimmed to 4" x 6" with vacuum pipe

Special Conditions: Possible 48 hours of running time with enhanced RF

TABLE I

The rate for proton production from Ta at I37°

Momentum Gev/c	N inter./2·IO^{11} pr/I g
0.4	II00
0.5	900
0.6	300
0.7	80
0.8	20
0.9	4
I.0	0.5

TABLE II

$\Delta P/p_o/_o$ summary for 2o degrees bend and 12 KG field

Protons					Pions				
P GeV/C	coul. scatt.	beam size	wire chamber	tof	P GeV/C	coul. scatt.	beam size	wire chamber	tof
400	8.3	1.33	8.4	3.6	400	3.4	1.3	3.7	
500	5.6	1.33	5.7	4.6	500	2.8	1.3	3.1	
600	4.3	1.33	4.5	5.8	600	2.3	1.3	2.7	
700	3.2	1.33	3.4	7.1	700	1.9	1.3	2.3	
800	2.5	1.33	2.8	8.6	800	1.5	1.3	2.0	
900	2.1	1.33	2.5	10.2	900	1.3	1.3	1.9	
1000	1.9	1.33	2.3	12.1	1000	1.3	1.3	1.9	

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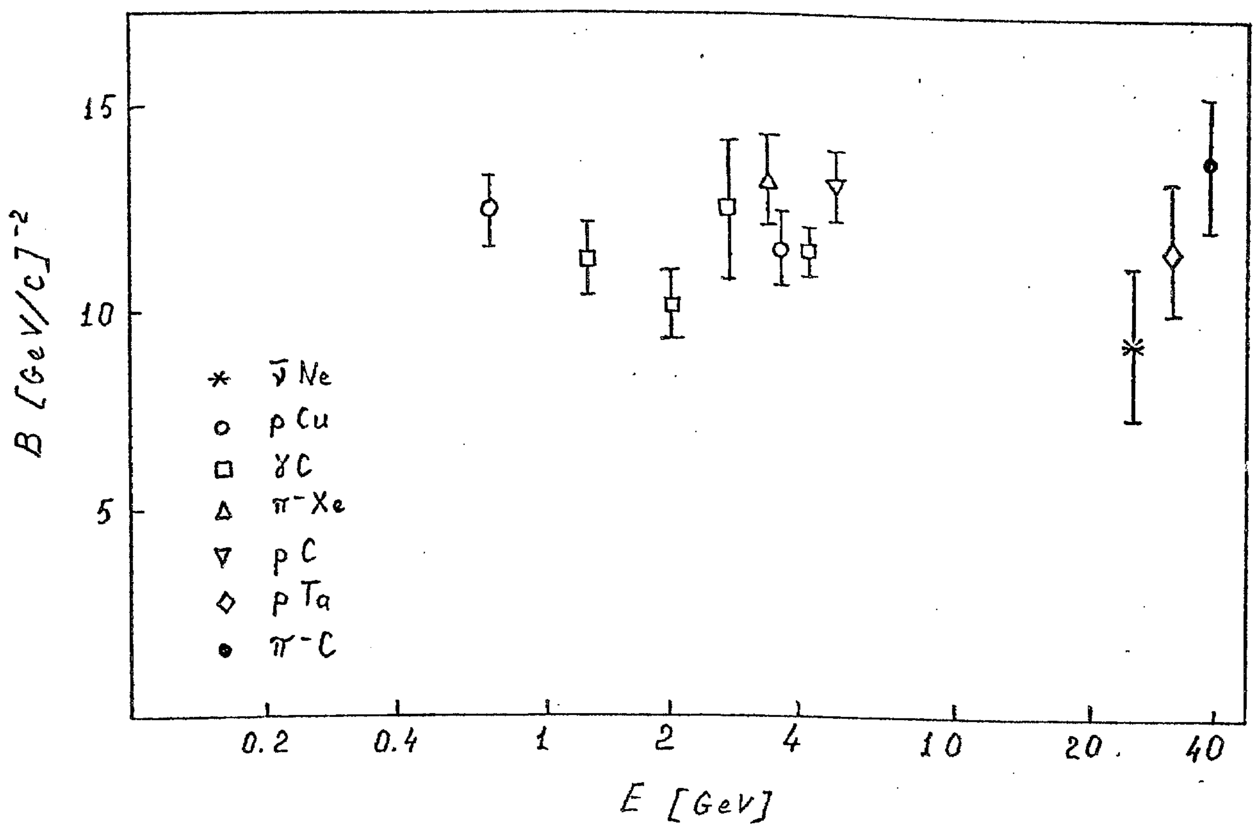


15
10
5
$B\ [GeV/c]^{-2}$
$\bar{\nu}$ Ne
p Cu
γ C
π^- Xe
p C
p Ta
π^- C
0.2
0.4
1
2
4
10
20
40
E [GeV]

Fig.I.

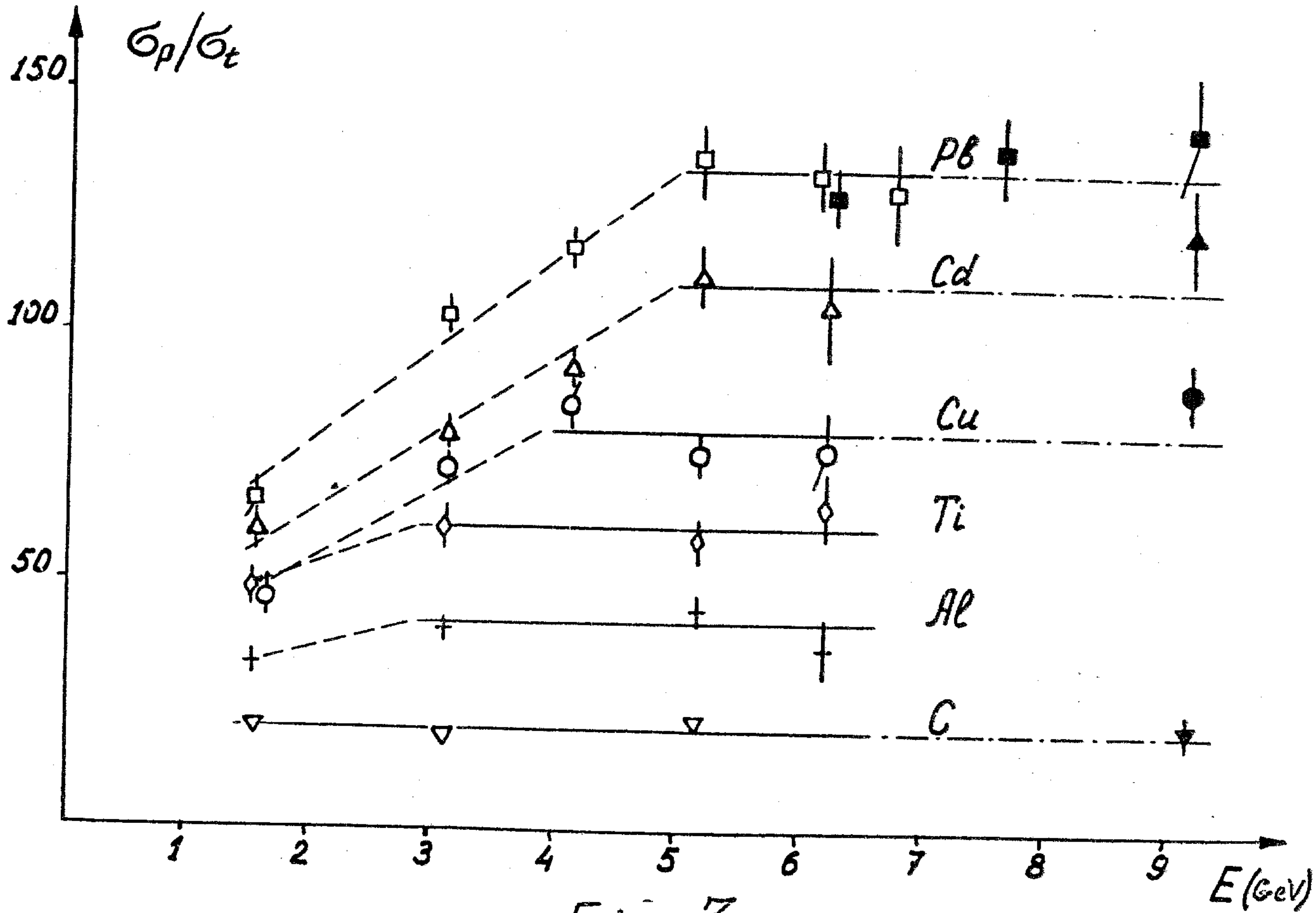


Fig. 3

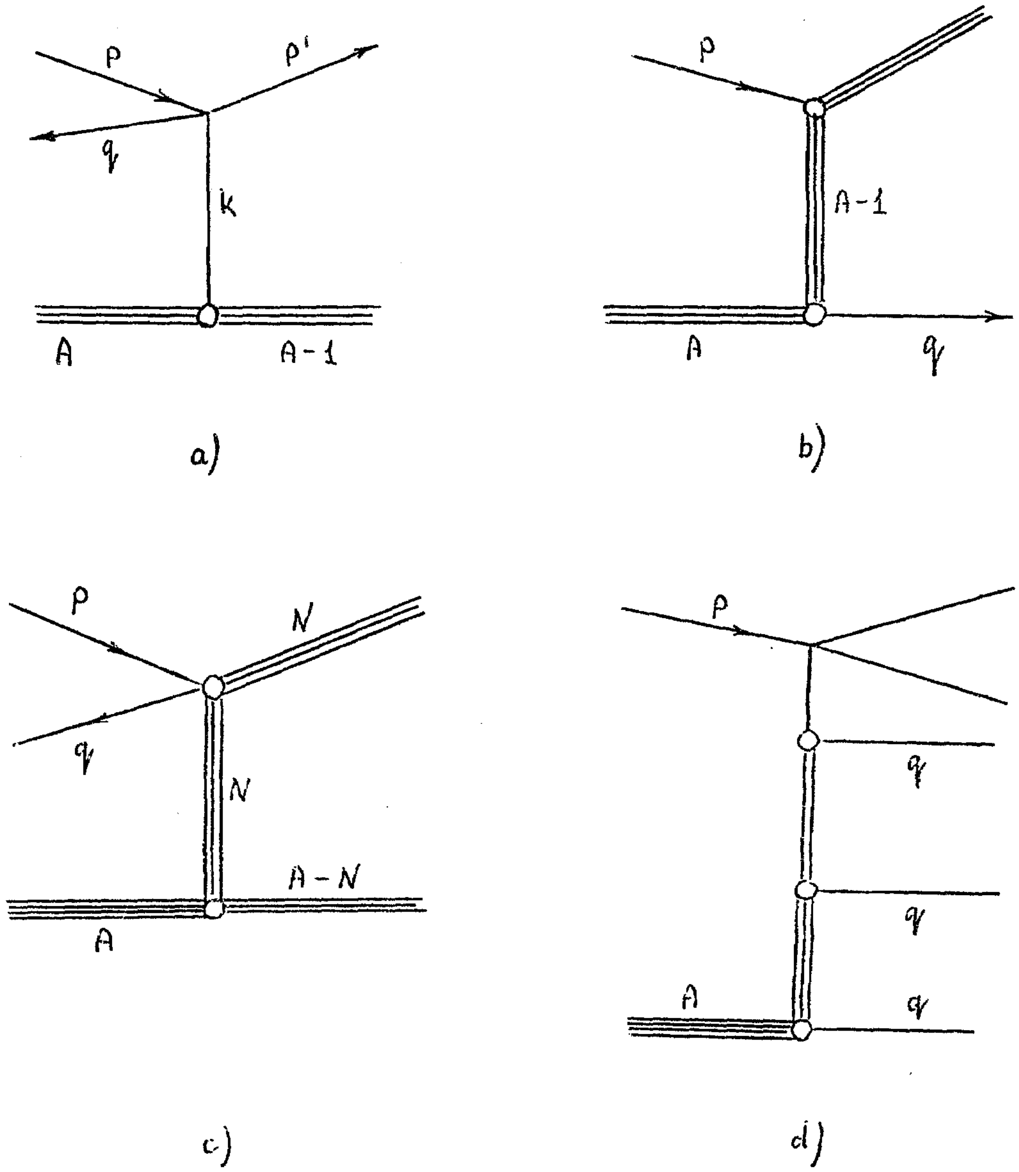


Fig.4.

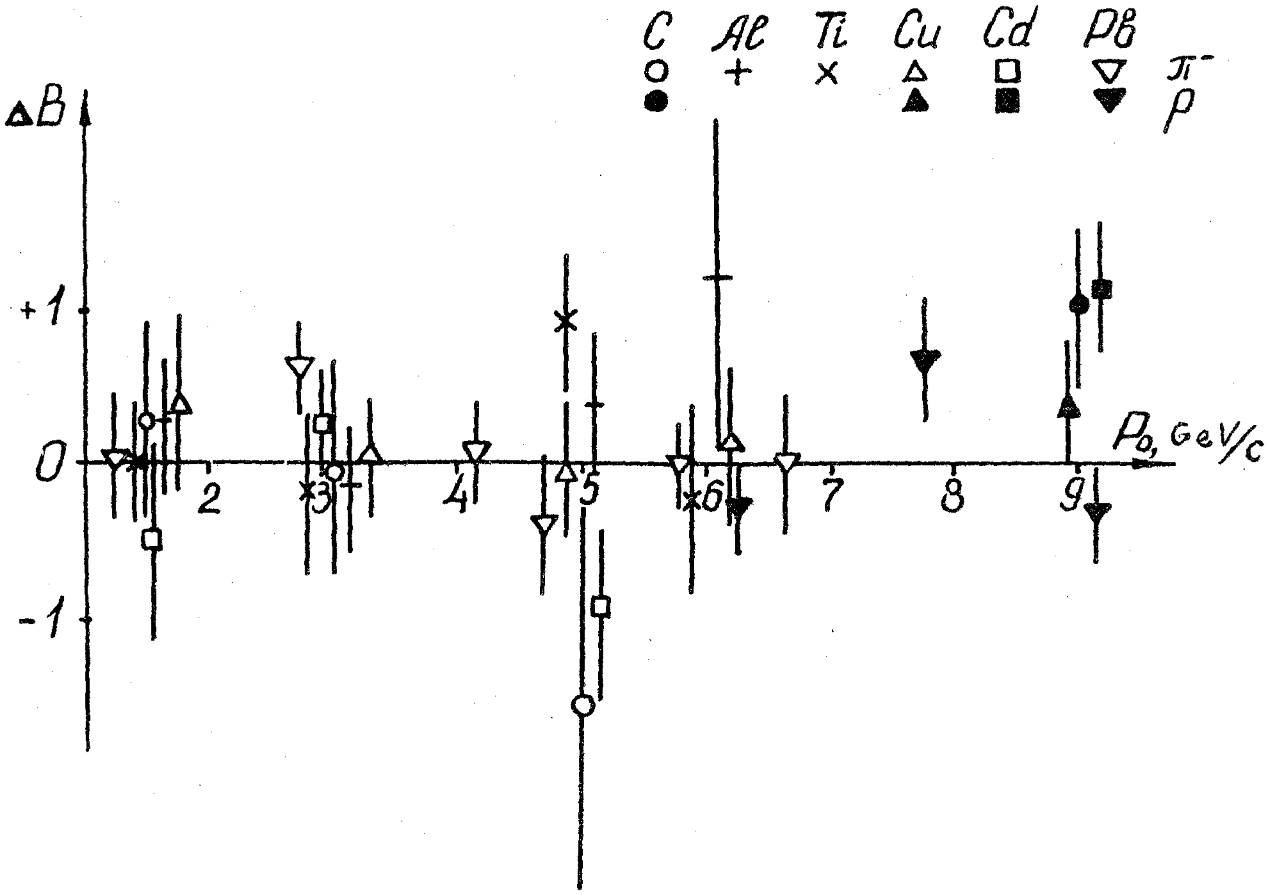
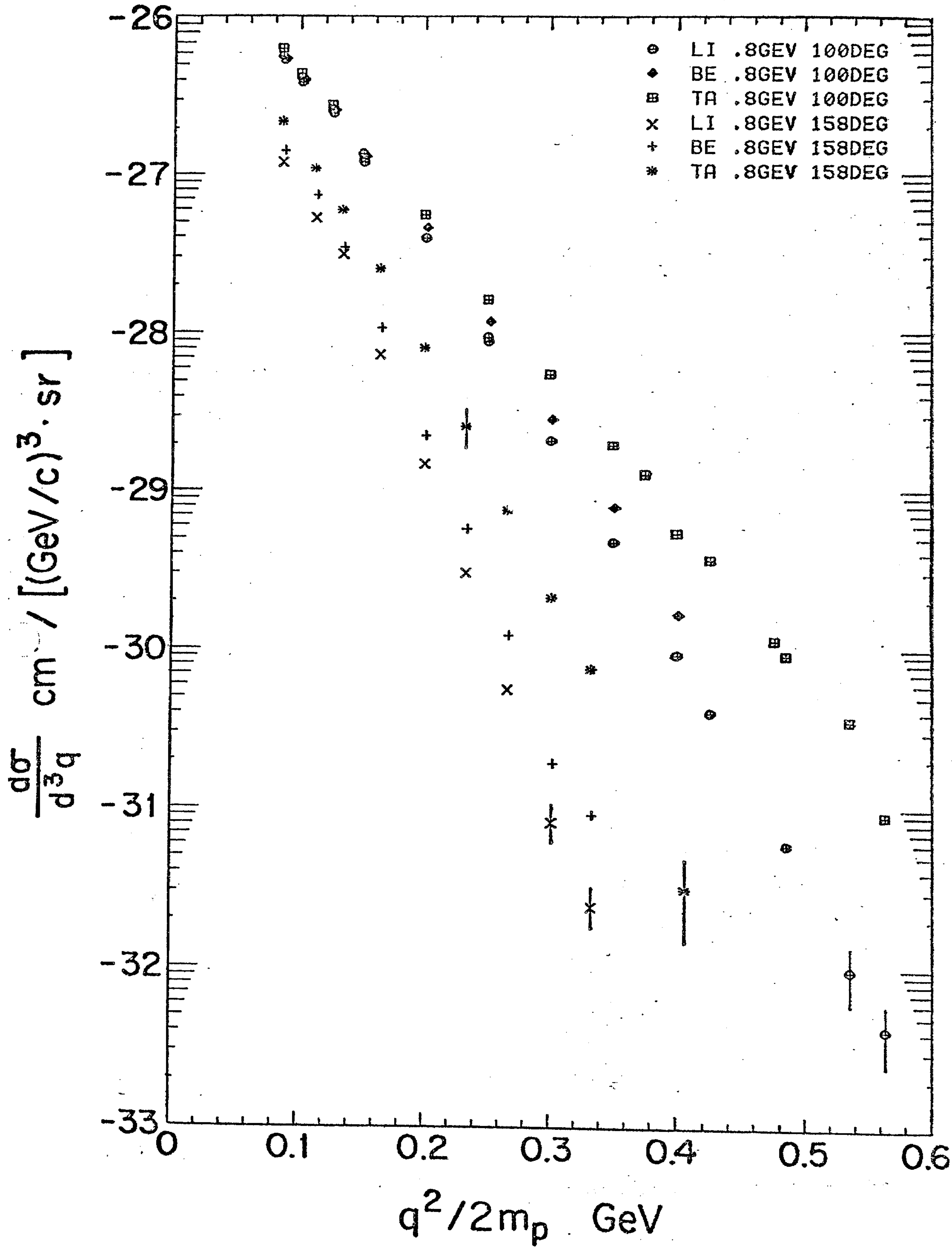
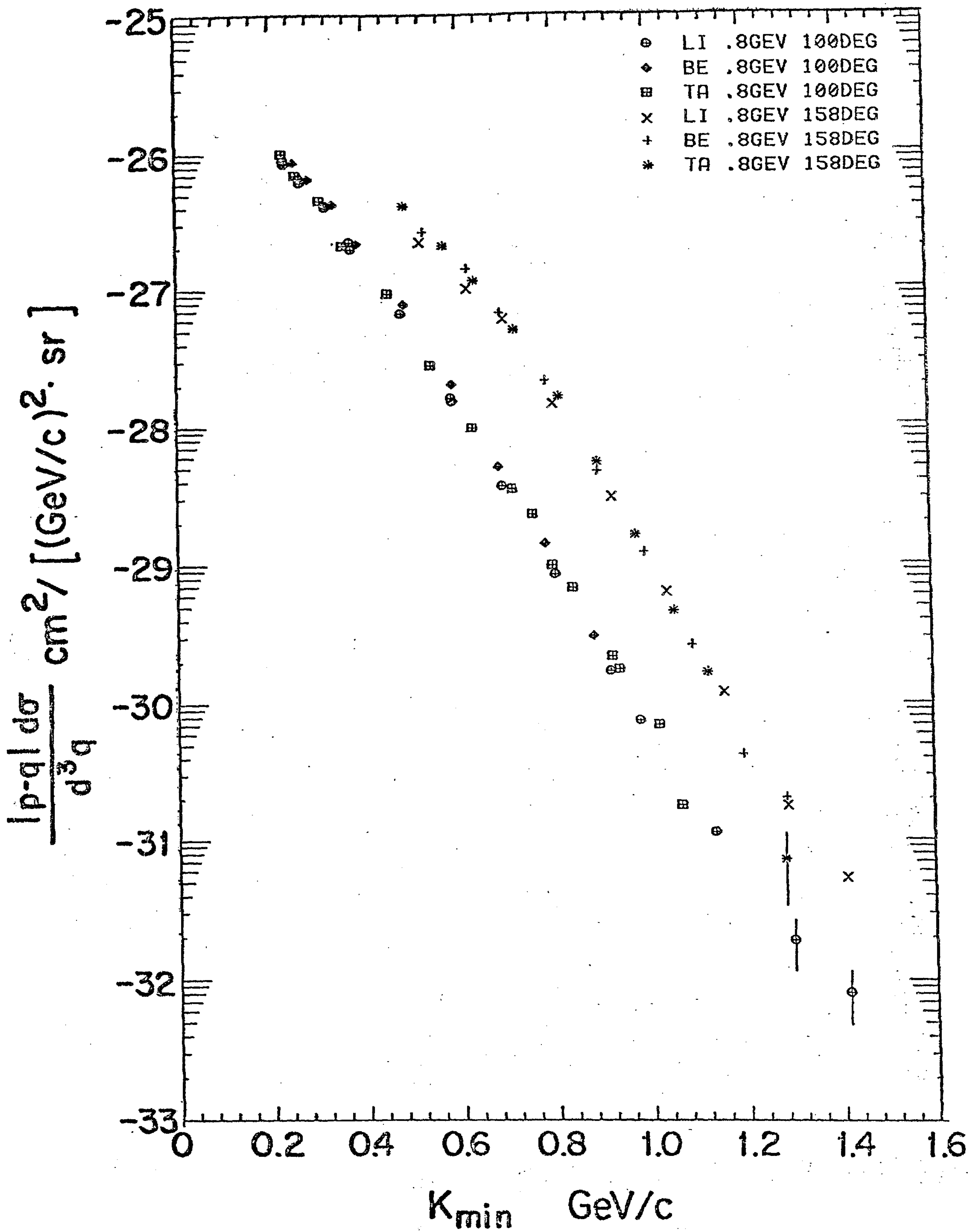


Fig. 2



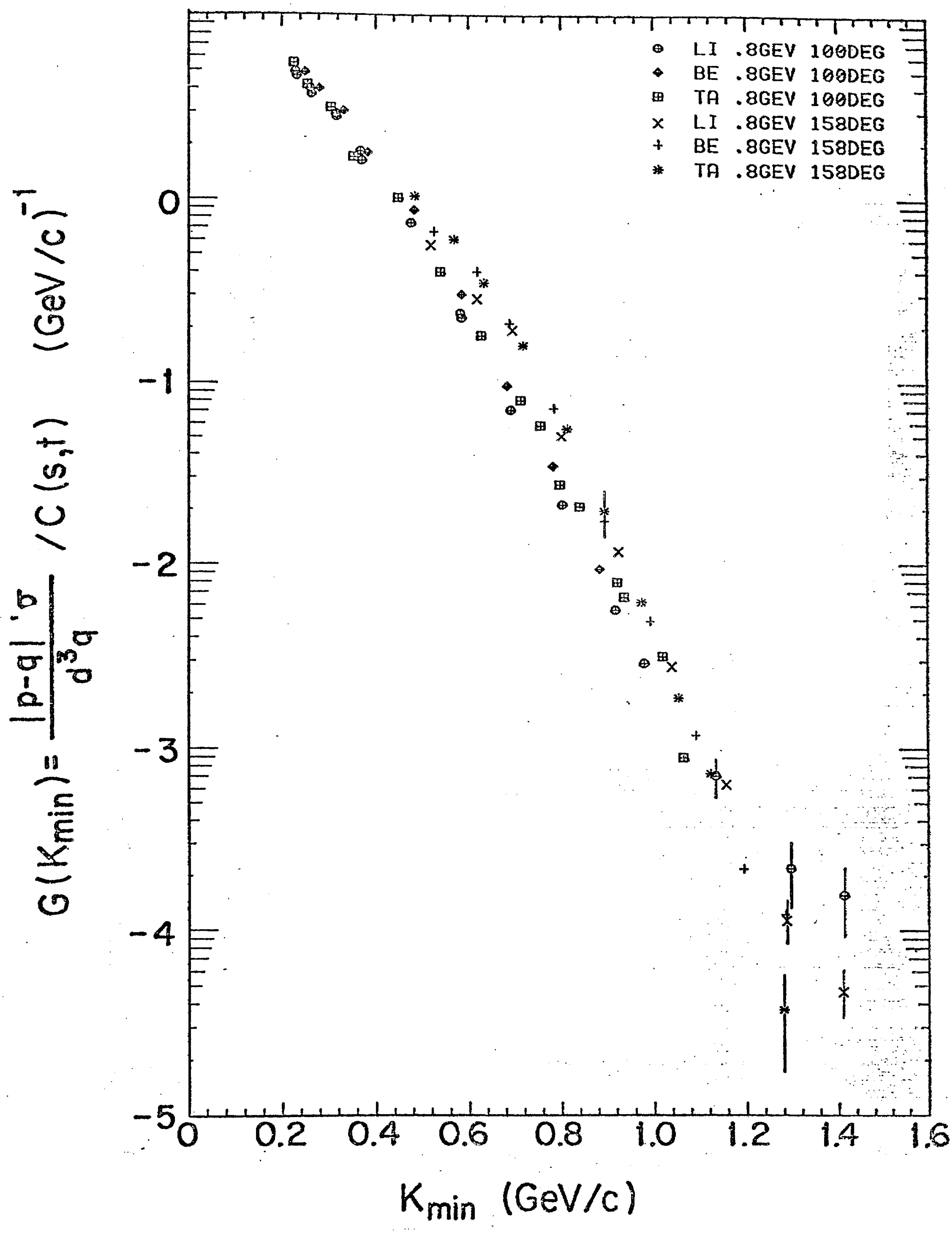
LI .8GEV 100DEG
BE .8GEV 100DEG
TA .8GEV 100DEG
LI .8GEV 158DEG
BE .8GEV 158DEG
TA .8GEV 158DEG
-26
-27
-28
-29
-30
-31
-32
-33
0
0.1
0.2
0.3
0.4
0.5
0.6
$\frac{d\sigma}{d^3q}$ cm / [(GeV/c)^3 · sr]
$q^2/2m_p$ GeV

Fig 5a.



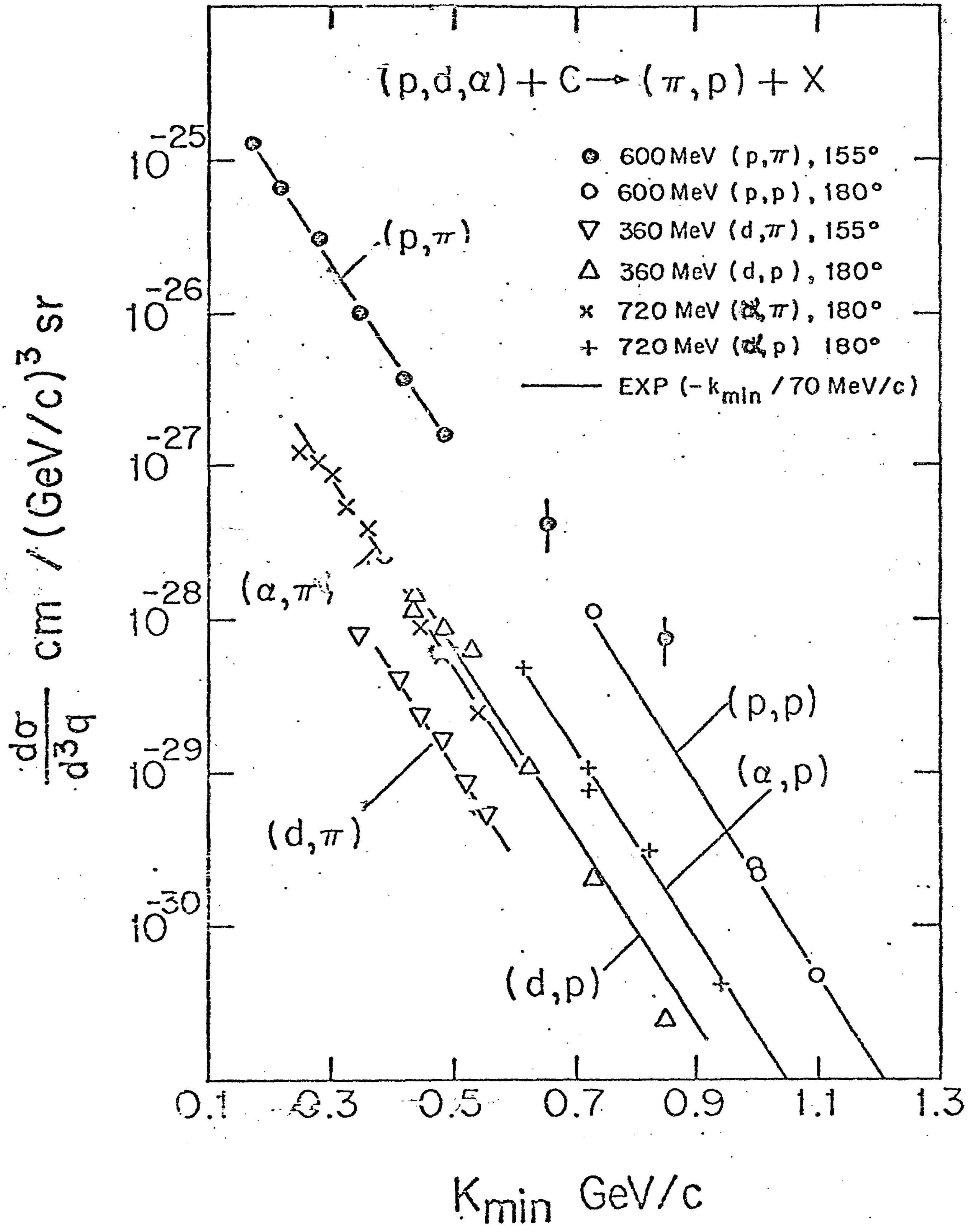
LI .8GEV 100DEG
BE .8GEV 100DEG
TA .8GEV 100DEG
LI .8GEV 158DEG
BE .8GEV 158DEG
TA .8GEV 158DEG
-25
-26
-27
-28
-29
-30
-31
-32
-33
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
$\frac{|p-q|\, d\sigma}{d^3q}$ cm^2/ [(GeV/c)^2· sr]
K_{min} GeV/c

Fig.5b.



LI .8GEV 100DEG
BE .8GEV 100DEG
TA .8GEV 100DEG
LI .8GEV 158DEG
BE .8GEV 158DEG
TA .8GEV 158DEG
$G(K_{min}) = \frac{|p-q|\,'\sigma}{d^3q} / C(s,t) \quad (GeV/c)^{-1}$
0
-1
-2
-3
-4
-5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
K_{min} (GeV/c)

Fig.5c.



(p,d,α) + C → (π,p) + X
600 MeV (p,π), 155°
600 MeV (p,p), 180°
360 MeV (d,π), 155°
360 MeV (d,p), 180°
720 MeV (α,π), 180°
720 MeV (α,p) 180°
EXP (-k_min / 70 MeV/c)
(p,π)
(α,π)
(d,π)
(p,p)
(α,p)
(d,p)
10^-25
10^-26
10^-27
10^-28
10^-29
10^-30
0.1
0.3
0.5
0.7
0.9
1.1
1.3
dσ/d^3q cm / (GeV/c)^3 sr
Kmin GeV/c

Fig,6.

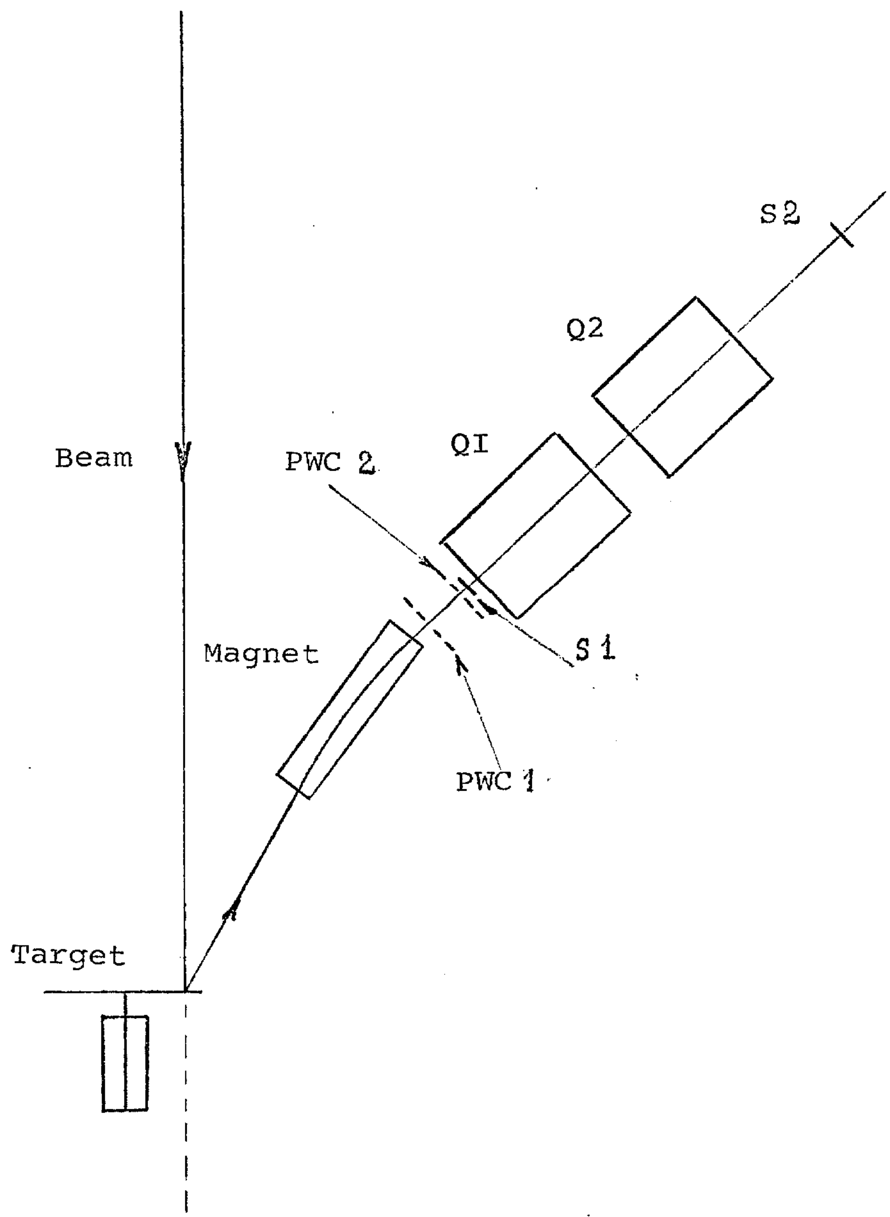


Fig.7.